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THE
JOURNAL OF GEOLOGY

FEBRUARY-MARCH 1920

THE ORIGIN OF GUMBOTIL

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The name gumbotil¹ was proposed recently for clays of distinctive characters which lie on glacial till and which are related closely to till. As originally defined, gumbotil is "a gray to dark colored, thoroughly leached, non-laminated, deoxidized clay, very sticky and breaking with starchlike fracture when wet, very hard and tenacious when dry, and which is chiefly the result of weathering of drift. The name is intended to suggest the nature of the material and its origin." In Iowa there is gumbotil on the Nebraskan, Kansan, and Illinoian drifts. It has not been developed on the Iowan drift nor on the Wisconsin drift.

SOME OF THE FORMER VIEWS REGARDING THE ORIGIN OF SUPER-
DRIFT CLAYS

Until recently these superdrift clays which are now called gumbotils had been found only on the Kansan and Illinoian drifts, in connection with which drifts the clays had been described under the name gumbo by several geologists.

Regarding the origin of this gumbo there have been various interpretations, some of which will be outlined briefly.

¹ George F. Kay, "Gumbotil, a New Term in Pleistocene Geology," *Science*, New Series, Vol. XLIV, November 3, 1916.

The gumbo of McGee.—Dr. W J McGee applied the name gumbo to the peculiar, tenacious clay which he found on his Lower Till,¹ and in referring to the habit of weathering of this till he states:²

Where the clay is plastic and sand free and of the usual blue color, as in the superior peripheral portion generally, it commonly weathers whitish or ashen to a limited depth and forms a tenacious, intractable soil, drowning when wet and baking when dry. This phase is colloquially known as “gumbo,” sometimes as “hardpan,” and locally as “white clay,” or (from its behavior below the plow) “push land.”

The gumbo of Leverett.—Mr. Frank Leverett in his monograph “The Illinois Glacial Lobe” described the gumbo which he found associated with the Illinoian and Kansan drifts in southeastern Iowa.³ He believed that the gumbo on the Illinoian drift was of the same age as that on the Kansan drift and favored the interpretation, although he was not satisfied fully with the view, that the gumbo is the result of aqueous deposition following submergence of the region.

The gumbo and loess-silt of Bain.—Dr. H. F. Bain, in his report on the geology of Decatur County, Iowa, states that blue to drab-colored gumbo which in places overlies the Kansan drift and is distinct from the drift belongs stratigraphically with the loess, and presents the view that the gumbo suggests a quiet-water deposit which has been compacted or puddled by water.⁴ In earlier geological reports of counties in Iowa the same author refers to similar material. In his report on Keokuk County, Iowa, he refers to a stiff, yellow to blue-gray, plastic, non-calcareous clay which is on the Kansan drift and beneath the loess on the uplands, and states:⁵ “It seems to be a deposit closely akin to the loess and

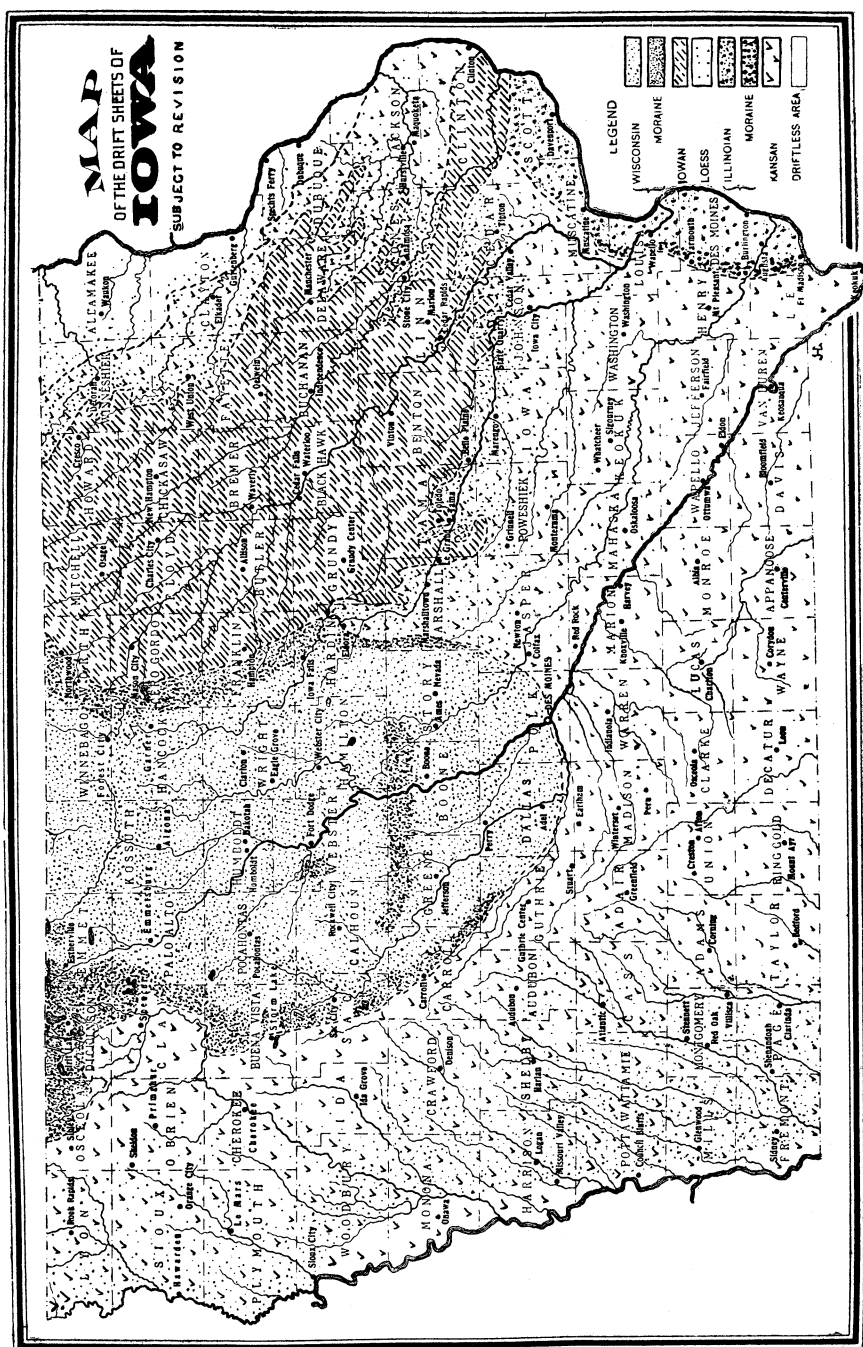
¹ Kansan drift of present classification.

² W J McGee, “The Pleistocene History of Northeastern Iowa,” *U.S. Geol. Surv., Eleventh Ann. Rept.*, Part I (1891), p. 509.

³ Frank Leverett, “The Illinois Glacial Lobe,” *U.S. Geol. Surv., Monograph XXXVIII* (1899), pp. 28–33.

⁴ H. F. Bain, “Geology of Decatur County, Iowa,” *Iowa Geol. Surv.*, Vol. VIII (1897), p. 292.

⁵ H. F. Bain, “Geology of Keokuk County, Iowa,” *Iowa Geol. Surv.*, Vol. IV (1894), p. 302.



probably genetically related to it. Very likely it is but a phase of that deposit though differing from it in its plasticity, color, and density." In his report on Appanoose County, Iowa, Dr. Bain describes a loess-silt¹ on Kansan drift which he considers to have been deposited later than the drift, and which in character and origin seems much like the white clays of Ohio Valley described by Leverett.²

In a geological report on Madison County, Iowa, Dr. H. F. Bain and Dr. J. L. Tilton refer to a dark-colored, impervious, unfossiliferous clay on Kansan drift as the lower of two phases of loess in the county.³

The gumbo of Udden.—Mr. J. A. Udden in a report on the geology of Pottawattamie County, Iowa, describes in considerable detail the gumbo or red clay associated with drift and makes the following statement regarding its origin:⁴

It would be premature at the present time to express any opinion as to the origin of this deposit. Probably it is mostly an old loess, which has been clogged up by interstitial deposition of fine ferruginous material through the agency of the ground water. Perhaps it is in part a fluvial deposit, made at a stage of semi-stagnant drainage, or possibly it is of varied origin, being in some places a surface wash, or a disintegration product derived from an underlying boulder clay, and at other places a modified upland loess, or a river silt.

The Dallas formation of Tilton.—Dr. J. L. Tilton gave the name Dallas deposits to gumbo and related materials overlying Kansan drift in southern Iowa. He considered the deposits to have been formed during the closing stages of the Kansan glacial epoch.⁵

The gumbo of Arey.—In a report on the geology of Davis County, Iowa, Professor M. F. Arey states that the gumbo which lies on the Kansan drift is perhaps a water deposit.⁶

¹ H. F. Bain, "Geology of Appanoose County, Iowa," *Iowa Geol. Surv.*, Vol. V (1895), pp. 407-8.

² Frank Leverett, "On the Significance of the White Clays of the Ohio Region," *American Geologist*, Vol. X (1892), pp. 18-24.

³ H. F. Bain and J. L. Tilton, "Geology of Madison County, Iowa," *Iowa Geol. Surv.*, Vol. VII (1896), p. 523.

⁴ J. A. Udden, "Geology of Pottawattamie County, Iowa," *Iowa Geol. Surv.*, Vol. XI (1900), p. 258.

⁵ J. L. Tilton, "A Pleistocene Section from Des Moines South to Allerton," *Iowa Acad. of Science*, Vol. XX (1913), pp. 218-20.

⁶ M. F. Arey, "Geology of Davis County," *Iowa Geol. Surv.*, Vol. XX (1909), p. 511.

The Loveland of Shimek.—Professor B. Shimek proposed the name Loveland formation¹ for gumbo-like deposits related to Kansan drift in Harrison, Monona, and adjacent counties in southwestern Iowa. Detailed descriptions of the formation are given in his report on the geology of Harrison and Monona counties.² Here he refers to the fact that Mr. Udden described similar material in Pottawattamie County as gumbo or red clay. It should be pointed out that the Loveland of Shimek differs in some important respects from the Kansan gumbotil of southern Iowa. The gumbotil is found only on glacial till and has a definite topographic position. According to Professor Shimek the Loveland in places lies not on till but on gravels. Moreover, it is not confined to a particular stratigraphic plain; the term has been applied to material in the lower part of the bluffs along the Missouri River in some places as well as to material 180 feet higher than the bases of the bluffs. Shimek considers the Loveland formation to be a water deposit which was formed during the stage of melting of the Kansan ice, and which has the same relation in general to the Kansan drift as have the Buchanan gravels to Kansan drift. This interpretation may, however, be somewhat open to question, as recent studies indicate.

The super-Kansan gumbo of Alden and Leighton.—In a recent publication by Dr. W. C. Alden and Dr. M. M. Leighton there is a discussion of super-Kansan gumbo in Iowa. The authors do not commit themselves definitely with regard to its origin, but they present evidence which they consider favorable to the view advanced by Kay that the gumbo is the residuum of thorough weathering and long leaching of the upper part of the Kansan till.³

Sufficient evidence has been submitted to show clearly that the students of superdrift clays—the gumbotils and related materials—have been far from agreement regarding their origin. Some geologists have considered these clays to be mainly of fluvioglacial origin, others believe that they are aqueous, and still others have

¹ B. Shimek, "Aftonian Sands and Gravels in Western Iowa," *Bull., Geol. Soc. Amer.*, Vol. XX (1910), p. 405.

² B. Shimek, "Geology of Harrison and Monona Counties," *Iowa Geol. Surv.*, Vol. XX (1909), pp. 371-75.

³ W. C. Alden and M. M. Leighton, "The Iowan Drift," *Iowa Geol. Surv.*, Vol. XXVI (1915), p. 91.

thought them to be related to loess. Until recently McGee was the only geologist who had stated definitely that the material which is now called gumbotil is the product of weathering of drift.

FIELD STUDIES OF GUMBOTILS AND RELATED MATERIALS

The conclusion which was presented by Kay in his paper in *Science* is:

. . . . that the gumbotil is the result chiefly of the chemical weathering of drift was reached only after the field relations of gumbotil had been studied carefully, and detailed chemical analyses of Nebraskan gumbotil, Kansan gumbotil, Illinoian gumbotil, and the glacial tills underlying these gumbotils had been made.

The field relations of Kansan gumbotil to the underlying Kansan till have been already briefly described.¹ The Kansan gumbotil, there called super-Kansan gumbo, reaches a maximum thickness of more than twenty feet, and is limited to tabular divides and other remnants of a gumbotil plain which, before it was affected by erosion, was as extensive, apparently, as the original Kansan drift plain. This gumbotil occupies a definite topographic position, and where it is exposed in railroad cuts it is seen to lie horizontally in the cut and not to conform to the surface slopes which have been developed by erosion. The gumbotil is dense, sticky, and very slippery when wet, but is hard and very tenacious when dry. It is usually dull gray to drab in color; in places the gray color is mottled with brown and reddish tints. It is leached, but in many places it contains lime concretions. The dry surfaces of the exposures of gumbotil are distinctly checked by sun cracks. It contains only a few small, scattered pebbles, which consist predominantly of quartz and chert and subordinately of crystallines and quartzites. A striking feature of the quartz and chert pebbles is their remarkably smooth surfaces. The gumbotil grades downward into yellowish to chocolate-colored till, in many places with numerous pebbles, few if any of which are calcareous. This oxidized and non-calcareous till, in turn, merges into unleached

¹ George F. Kay, "Some Features of the Kansan Drift in Southern Iowa," *Bull., Geol. Soc. Amer.*, Vol. XXVII, pp. 115-17; reprinted in *Iowa Geol. Surv.*, Vol. XXV, pp. 612-15.

till, oxidized yellowish for several feet vertically, below which is the normal, unoxidized and unleached, dark grayish to bluish-black Kansan till. An impressive feature of the unleached, oxidized till is the presence of numerous concretions of calcium carbonate, the lime of the concretions having been dissolved in connection with the formation of the overlying gumbotil and leached till, carried downward and later precipitated.

Some sections showing the relations of Kansan gumbotil to underlying Kansan drift.—The following sections are given as typical of many sections that have been studied at widely separated places in the Kansan-drift areas of Iowa. They are intended to show the intimate field relations of the Kansan gumbotil to the underlying till.

Section in cut on the Chicago, Milwaukee & St. Paul Railway about one mile east of Foster Station, in the southeast corner of Monroe County, Iowa:

	Feet	Inches
5. Soil, black, porous.....	2	
4. Loesslike clay, chocolate-colored, leached....	1	6
3. Loesslike clay, light-colored, grayish; on dry surface looks like gumbotil; has chocolate-colored stains; sticky when wet; contains a few small siliceous pebbles; leached.....	5	6
2. Gumbotil (Kansan), gray-colored, in lower part chocolate-colored; few pebbles; starch-like fracture when wet; leached.....	12	
1. Glacial till (Kansan), brown color, with very irregular patches of gray-colored till resembling gumbotil; dry surface of the till is brownish yellow; damp surface is chocolate-colored; few pebbles; leached to base of cut	5	

Section in cut on the Chicago, Burlington & Quincy Railway at mile 372, one mile west of Murray Station, Clarke County, Iowa:

	Feet
4. Loesslike clay, gray to pale-yellowish color, with irregular lines of brown on dry surface; when damp it is grayish with mottling of yellow to brown colors; stands vertically, upper few feet mealy.....	15

	Feet
3. Gumbotil (Kansan), gray to drab in color, sticky when wet, hard and tenacious when dry; contains a few siliceous pebbles; leached	11
2. Glacial till (Kansan), oxidized and leached	4
1. Glacial till (Kansan), oxidized and unleached; has many lime concretions	11

Section in cut on Chicago, Milwaukee & St. Paul Railway on the divide about three miles west of Templeton, Carroll County, Iowa:

	Feet	Inches
4. Loess		
Buff-colored, leached	15	
Buff-colored, unleached	10	
3. Gumbotil (Kansan), gray to dark-drab to chocolate-colored, upper few feet reddish, a few small siliceous pebbles	20	6
2. Glacial till (Kansan), oxidized yellow to buff, leached, closely related to No. 3		
1. Glacial till (Kansan), oxidized, unleached; many calcareous concretions	8	

Section in cut on Santa Fe Railway east of New Boston, Lee County, Iowa:

	Feet
4. Loesslike clay, top 2 feet very light gray; below, yellow to light-brown on dry surface; when freshly cut into, more chocolate-colored; a joint clay; grades into No. 3	12
3. Gumbotil (Kansan), typical; gray on dry surface and has a checked appearance; when freshly cut into, has a more drab color; very sticky; contains some spots of brown; contains small siliceous pebbles; leached; grades into No. 2	12
2. Glacial till (Kansan), oxidized and leached; contains patches of gray similar to the gumbotil; many pebbles; grades into No. 1	5
1. Glacial till (Kansan), oxidized and unleached; contains many pebbles and small boulders; many calcareous concretions; to the bottom of the cut, exposed	27

In all of these sections the zone of oxidized and leached till beneath the gumbotil is narrow. A study of thirty-five sections widely separated as to location shows that in eighteen of them the zone of oxidized and leached Kansan till beneath the Kansan gumbotil is 5 feet. In twelve of them it is 5 feet 6 inches; in the remaining sections the zone is somewhat more than 5 feet 6 inches or slightly less than 5 feet. The uniform thickness of the leached zone is impressive. The thickness of the oxidized, unleached zone of Kansan till is about 40 feet.

The distribution of Kansan gumbotil in Iowa.—The relations of Kansan gumbotil to the underlying Kansan till have been seen at scores of places in southern Iowa and at many places in other parts of the state. In fact the Kansan gumbotil has been studied in every county of three tiers of counties in southern Iowa as well as in many of the counties which are farther north.¹ Moreover, within the Iowan-drift area the Kansan gumbotil has been found beneath Iowan drift at numerous places.² It will be of interest to state that the Kansan gumbotil is now known at a sufficient number of places in Iowa to permit the restoration of the Kansan gumbotil plain, that is, the original plain surface of the weathered Kansan till, as it was in Iowa before any great erosion was accomplished.

Some sections showing the relations of Nebraskan gumbotil to underlying Nebraskan drift.—The field relations of the Nebraskan gumbotil to the underlying Nebraskan till are similar to the relations that have been described as existing between the Kansan gumbotil and the underlying Kansan till. The two tills, the Nebraskan and the Kansan, are much alike lithologically and both appear to have undergone similar changes under similar conditions. Below the Nebraskan gumbotil there is, as in the case of the Kansan gumbotil, a narrow zone of leached, oxidized till which grades downward into unleached, oxidized till with many concretions.

¹ George F. Kay, "Pleistocene Deposits between Manilla in Crawford County and Coon Rapids in Carroll County, Iowa," *Iowa Geol. Surv.*, Vol. XXVI (1917), pp. 215-31.

² W. C. Alden and M. M. Leighton, "The Iowan Drift, a Review of the Evidences of the Iowan Stage of Glaciation," *Iowa Geol. Surv.*, Vol. XXVI (1917), pp. 92-109.

A good section to show the field relations of the Nebraskan gumbotil to the underlying Nebraskan till is a railroad cut just east of a viaduct $1\frac{1}{2}$ miles west of Manning, Carroll County, Iowa.¹ From the surface the cut shows loess, Kansan till, soil band, Nebraskan gumbotil, and Nebraskan till. The section is as follows:

	Feet	Inches
6. Loess:		
Leached, yellowish-gray on dry surface; yellowish-brown to buff-brown on damp surface; no shells or concretions.....	7	
Unleached, lighter-colored on dry surface than the leached loess, and when damp is buff with gray streaks; contains shells and concretions.....	5	
5. Glacial till (Kansan), yellow, unleached, with calcareous concretions; numerous pebbles including granites, quartzites, etc. Below the oxidized, unleached till is gray till with a few pebbles. It is gumbotil-like, but effervesces freely. It was probably picked up from the gumbotil zone below.....	5	
4. Soil band containing carbonaceous material..		4
3. Gumbotil (Nebraskan), gray to drab-colored, few pebbles. The upper 6 feet is fine grained, gray, and is less sticky and gumbotil-like than the lower 7 feet, which is leached but has some calcareous concretions.....	13	
2. Glacial till (Nebraskan), oxidized, apparently leached, but has calcareous concretions, upon which are films of manganese dioxide.....	2	
1. Glacial till (Nebraskan), unleached, oxidized, light-yellowish color on dry surface, mottled brownish with gray when damp; many calcareous concretions, especially in upper 10 feet.....	17	

In Taylor County, Iowa, at a stream crossing just west of Conway Station on the Chicago, Burlington & Quincy Railway, is an exposure at which the following section was observed:

¹ George F. Kay, "Pleistocene Deposits between Manilla in Crawford County and Coon Rapids in Carroll County, Iowa," *Iowa Geol. Surv.*, Vol. XXVI (1917), p. 225.

	Feet	Inches
4. Loesslike clay.....	1	
3. Gumbotil (Nebraskan), grayish to drab on dry surface; when damp, is grayish to brownish; a few siliceous pebbles; leached.....	11	
2. Glacial till (Nebraskan), oxidized and leached, many disintegrated bowlders.....	4	6
1. Glacial till (Nebraskan), oxidized, unleached, concretions, exposed.....	3	

Near this exposure Kansan till overlies the Nebraskan gumbotil.

Another interesting cut which shows Nebraskan gumbotil and underlying drift is along the wagon road west of Osceola, Clarke County, southwest corner of section 13, Ward Township, in front of a schoolhouse. The section is as follows:

	Feet	Inches
5. Loesslike clay, gray to light-yellow.....	8	
4. Glacial till (Kansan), oxidized, leached, ferretto zone on top.....	5	6
3. Glacial till (Kansan), oxidized, unleached, many concretions.....	8	
2. Gumbotil (Nebraskan), gray to drab-colored, sticky when wet, tough when dry, some calcareous concretions, a few siliceous pebbles; leached.....	10	
1. Glacial till (Nebraskan), oxidized, unleached; except in narrow upper zone, many calcareous concretions; bowlders and pebbles; above base of exposure.....	25	

Southeast of New Market and near the middle of the north boundary of section 5, Mason Township, Taylor County, Iowa, is a fine exposure of Nebraskan gumbotil with Kansan drift above it and Nebraskan drift below it. The section is as follows:

	Feet
4. Drift (Kansan), oxidized and unleached, many concretions.....	15
3. Gumbotil (Nebraskan), gray to drab-colored, leached, a few siliceous pebbles.....	8
2. Glacial till (Nebraskan), oxidized, leached..	3
1. Glacial till (Nebraskan), oxidized, unleached, many calcareous concretions, exposed.....	22

The distribution of Nebraskan gumbotil in Iowa.—The Nebraskan gumbotil has been found in widely separated localities in Iowa. Among the many counties in which it has been studied are Decatur, Clarke, Warren, Madison, Union, Ringgold, Taylor, Adams, Adair, Cass, Montgomery, Page, Shelby, Crawford, Carroll, Tama, and Johnson counties. The topographic positions of the several outcrops indicate that the Nebraskan gumbotil was formed on an extensive plain with slight relief just as in the case of the formation of the Kansan gumbotil. The maximum thickness of Nebraskan gumbotil thus far studied is about thirteen feet. The zone of oxidation of the Nebraskan drift is rarely fully exposed; depths of oxidation of more than forty feet have been seen without the base of the zone of oxidation having been revealed.

Some sections showing the relations of Illinoian gumbotil to underlying Illinoian drift.—That the relations of the Illinoian gumbotil to the underlying Illinoian till are similar to the relations of Kansan and Nebraskan gumbotils to their respective tills may be shown by presenting two sections from many sections which are known to show similar relationships.

An exposure at the head of a ravine about one hundred yards north of the edge of the bluff north of Fort Madison, Lee County, gives a section as follows:

	Feet	Inches
4. Loess and loesslike clay, grayish-yellow to buff-yellow in color.	7	
3. Gumbotil (Illinoian), drab to chocolate to dark color, starchlike fracture, few pebbles, leached; grades into No. 2.	4	6
2. Glacial till (Illinoian), oxidized, leached.	6	
1. Glacial till (Illinoian), oxidized, unleached to base of gulch.	15	

A splendid section to show, not only the Illinoian gumbotil and underlying Illinoian drift, but also the Kansan gumbotil and underlying Kansan drift, is a railroad cut on the Chicago, Milwaukee & St. Paul Railway between Fort Madison and Sawyer, in Lee County. The cut is in section 28, Washington Township, and shows the following materials:

	Feet	Inches
6. Gumbotil (Illinoian), gray to ashen-color on dry surface; on fresh surface, gray mottled with brown; small pebbles; leached; grades into No. 5.....	4	6
5. Glacial till (Illinoian), oxidized brownish, contains boulders, leached.....	5	6
4. Glacial till (Illinoian), oxidized, unleached, has concretions, breaks into irregular shaped fragments.....	1	
3. Gumbotil (Kansan), drab to dark color, starchlike fracture, some calcareous concretions; few pebbles; leached; grades into No. 2	8	6
2. Glacial till (Kansan), oxidized, pebbles and boulders, leached.....	5	
1. Glacial till (Kansan), oxidized, unleached, many concretions, breaks with irregular fracture, exposed.....	12	

The transition zone between gumbotil and the base of the oxidized leached drift.—Many interesting sections might be given to show disintegrated and decomposed boulders in the transition zone between gumbotil and the base of underlying leached and oxidized till. For example, on the east-west wagon road in section 1, Otter Creek Township, Lucas County, Iowa, there is in the transition zone between the Kansan gumbotil and the base of the leached, oxidized Kansan till a granite boulder with dimensions of 4×2 feet on the slope. It is so thoroughly weathered that its outlines are discerned only with difficulty. Again, in a cut through the upland $\frac{1}{4}$ mile north of Forbush on the interurban railway between Centerville and Moravia, Appanoose County, Iowa, there is in the transition zone between Kansan gumbotil and the base of the oxidized, leached Kansan till a completely disintegrated granite boulder 5 feet long by 2 feet wide as exposed on the surface.

The pebble content of gumbotil and underlying drift.—The gumbotils and underlying tills were studied also with regard to their pebble content to ascertain whether or not additional evidence could be obtained to strengthen the view that the gumbotils are the result of changes in what was originally till.

The average pebble content of Kansan gumbotil gained from eight analyses of pebbles made in widely separated areas in Iowa is as follows:

	Percentage
Quartz	48.5
Chert, flint, etc.	31.8
Quartzite	6.8
Granite	7.8
Basalt and greenstone	2.9
Feldspar	1.0
Sandstone	0.5

It will be seen that more than 87 per cent of the pebbles are of siliceous material; the highest percentage of siliceous pebbles shown by any of the exposures of Kansan gumbotil subjected to study was 98 per cent, the lowest 75 per cent.

The average pebble content of the leached and oxidized Kansan till beneath the Kansan gumbotil is as follows:

	Percentage
Quartz	16.8
Chert, flint, etc.	16.5
Quartzite	8.0
Granite	20.3
Basalt and greenstone	24.5
Feldspar	1.0
Felsite	7.0
Sandstone	1.0
Shale	0.6
Quartz porphyry	0.5
Schist	2.3
Gneiss	0.3

The average content of siliceous pebbles is here only about 42 per cent, compared with 87 per cent in the Kansan gumbotil; the highest siliceous content was about 55 per cent, the lowest about 25 per cent.

A study of the pebble content of the unleached and oxidized Kansan till beneath the leached and oxidized Kansan till gave an average result as follows, seven analyses being used:

	Percentage
Quartz	6.4
Chert, flint, etc.	8.3
Quartzite	3.0

	Percentage
Limestone	40.0
Granite	11.0
Basalt and greenstone	27.0
Felsite	3.0
Sandstone	1.0
Slate	0.4
Schist	0.4

It is clearly seen that the content of siliceous pebbles of the unleached and oxidized Kansan till is considerably less than that of the leached and oxidized Kansan till, the average siliceous content of the former being less than 20 per cent.

It is of interest to note that the kinds of pebbles found in the different zones of material are much alike. Of course limestone is in the unleached zone only.

Similar results were obtained when the Nebraskan and Illinoian gumbotils and their respective underlying tills were studied. For instance, the average pebble content obtained from several analyses of Nebraskan gumbotil is as follows:

	Percentage
Quartz	36.75
Chert, flint, etc.	21.25
Quartzite	20.25
Granite	8.25
Basalt and greenstone	11.0
Feldspar	1.25
Felsite	0.50

The content of siliceous pebbles is here more than 78 per cent; none of the Nebraskan gumbotil examined gave less than 72 per cent, and the highest gave 88 per cent. The studies of leached and oxidized Nebraskan till gave about 38 per cent of siliceous pebbles, and the unleached and oxidized Nebraskan till gave about 15 per cent of siliceous pebbles.

Analyses of the pebbles of Illinoian gumbotil gave an average result as follows:

	Percentage
Quartz	43
Chert, flint, etc.	53
Quartzite
Granite
Basalt and greenstone	2
Sandstone	2

Analyses of pebbles of leached and oxidized Illinoian till beneath Illinoian gumbotil gave results as follows:

	Percentage
Quartz	28
Chert, flint, etc.	38
Quartzite
Granite	12
Basalt and greenstone	14
Feldspar	2
Felsite	5
Sandstone	1

These analyses show also that the percentage of siliceous pebbles in the gumbotil is much higher than that in the oxidized and leached till which underlies it.

The sizes of pebbles in gumbotil and underlying drift.—When pebbles from the gumbotils and underlying tills were being taken in the field the only purpose in mind was to ascertain the percentage content of the different constituents. Later, when these studies were being made in the laboratory, it became evident that the pebbles might also be used in estimating the relative sizes of the pebbles in the different horizons, and in determining the shapes of the pebbles.

One hundred pebbles collected from the Nebraskan gumbotil at one locality had dimensions as follows: largest pebble $2.4 \times 1.4 \times 1$ cm., smallest pebble 2 mm., and average pebble 8×5 mm. The shapes of these pebbles were subangular to spheroidal. The unleached and oxidized Nebraskan drift beneath the Nebraskan gumbotil had pebbles with dimensions as follows: largest pebble $6.25 \times 4.5 \times 1.75$ cm., smallest pebble 3×4 mm., and average pebble $1.75 \times 1.5 \times 1$ cm. The pebbles were chiefly flat and subangular; some were slightly rounded.

The largest pebble in the Nebraskan gumbotil from another locality was $10 \times 7 \times 5$ mm., the smallest 1.5×2 mm., and the average 3 mm.; the shapes were subangular to spheroidal. Here the underlying Nebraskan till had pebbles, the largest pebble of which was $5.5 \times 3.5 \times 3$ cm., the smallest pebble 3×2 mm., and the average pebble $1.5 \times 1 \times .75$ cm. The shapes of the pebbles were subangular to more or less flat.

Similar studies made of pebbles taken from Kansan gumbotil and from underlying Kansan drift gave results as follows: largest pebble in gumbotil 3.2 cm., smallest pebble 3 mm., and average pebble 7 mm. In the underlying drift there are many pebbles 10-12 cm. in diameter, a few more than 3 cm. in diameter; the smallest pebble seen was 7 mm., and the average of one hundred pebbles collected was about 1.8 cm. The shapes of the pebbles were similar to corresponding horizons in the Nebraskan materials.

CHEMICAL STUDIES OF GUMBOTIL AND RELATED MATERIALS

In addition to a study of the field relations of Nebraskan gumbotil, Kansan gumbotil, and Illinoian gumbotil, the tills which underlie these gumbotils, and laboratory studies of the physical properties of these materials, there were made detailed chemical analyses of gumbotils and related materials. The specimens were taken from exposures which had been studied carefully in the field, and the materials selected were thought to represent satisfactorily the compositions of the zones from which they were taken. The analyses were made from 1-gm. samples of fine material which had been separated carefully from pebbles and concretions. Only the material which could be sifted through a "twenty-mesh" copper-gauze sieve was pulverized and subjected to chemical analysis. Accurate determinations were limited to the oxides of aluminum, silicon, iron, calcium, and magnesium, since deductions as to the nature of the chemical processes involved in the transformation of the drift can be made only upon the proportions of these less mobile constituents now present. The analyses were made in strict accord with the preferred methods and the recommendations prescribed by Hildebrand.¹

Before referring in detail to the kinds of materials which were analyzed, the localities from which they were taken, and the results of the analyses, it seems well to discuss somewhat fully some of the geo-physico-chemical factors which need to be understood in order to interpret correctly whether or not a material such as gumbotil is the product of weathering of till. Chemical evidence will be presented to support the field evidence that the

¹ Hildebrand, "The Analysis of Silicate and Carbonate Rocks," *U.S. Geol. Surv., Bulletin* 422.

gumbotils and underlying oxidized and leached tills have been formed by chemical weathering and leaching of till which was originally unoxidized and unleached.

The abundant field evidence supporting this theory has been presented. Emphasis has been put upon the gradation of gumbotil into underlying till, the variations in the sizes of pebbles in the related zones, and the presence of remnants of thoroughly disintegrated and decomposed boulders in the transition zone between gumbotil and oxidized and unleached till.

There have been profound changes involving chemical processes which operated during immense lengths of time, and which occurred long ages ago. These chemical processes are subject to a few definite, general physical laws of nature which are independent of time or place. The laws of stress and strain, of the degradation of energy, of hydrolysis, of mass-action, or of solution in general are as lasting as the universe itself.

The rôle of water in geochemical changes.—The dominant factor in all of these geo-physico-chemical changes is water, more especially the aerated water. When the rain falls upon the ground one part, the “run-off,”¹ flows over the surface and escapes by way of the natural drainage channels. It is this form which produces erosion. A second part, the “fly-off,” immediately evaporates into the air, while the third part, the “cut-off,” penetrating the soil by way of the soil interstices, flows downward under the influence of gravity. Of these the cut-off water is the only form which is directly effective in geochemical transformations. It moves through the soil and its substrata with comparative rapidity, reappearing elsewhere as seepage water or as springs.

The rain and surface waters contain dissolved oxygen, nitrogen, and carbon dioxide, each in proportion to its partial pressure in the atmosphere. The chemical and physical processes which are continually taking place below the surface involve the absorption and formation of carbon dioxide and the disappearance of oxygen and nitrogen. These gases impart to the soil an atmosphere, and their concentrations in the soil solution follow more or less slowly the barometric changes above the surface. The soil bacteria and

¹ This terminology was proposed by McGee.

other lower forms of life are likewise producing change and undergoing change continually.

According to Cameron¹ the water within the soil is in reality of two kinds, namely, "film" water and "free" water. When a relatively small quantity of water is added to an absolutely dry soil or powdered solid there is some shrinkage in the apparent volume of the solid; the water spreads over the surface in the form of a film. With further addition of water the apparent volume of the solid material increases until a maximum is reached. The optimum water content which gives the maximum volume is a definite, critical, physical, characteristic property for a given soil or solid. A further addition of water will not increase the thickness of the soil film but will produce free-water in the soil interstices.

These two kinds of water play an important rôle. The film-water is tenaciously held by the soil and subsoil particles. In dry seasons it is practically a saturated solution of the dissolved rock and soil materials. When the surface of the ground becomes flooded, as in wet seasons or during heavy rains, the downward-moving free-water extracts and carries away a part of the mineral content of the film solution. Obviously the proportions of water-soluble materials in soils containing moving free-water should be, and are, less than those in soils containing only film-water. This was conclusively shown by Hilgard.² In the humid regions there is a greater amount of rainfall, hence a greater amount of downward-moving free-water, consequently a greater amount of leaching.

Once the free-water is removed the saturation of the film-water repeats. In this film-water are the dissolved rock materials, the carbon dioxide, the oxygen, the nitrogen, the soluble humous material, and the soil bacteria. Between these are evolved all of the processes leading to the disintegration of the rock material and the formation of the soil and its substrata.

Chemical nature of glacial materials.—The rock materials transported by the glaciers consisted chiefly of silicates, quartz, some clays, and other previously weathered materials. The complex silicates are salts of a very weak acid—silicic acid, with various

¹ Cameron, *Jour. Phys. Chem.*, Vol. XIV (1910), p. 340.

² See Merrill's *Rock Weathering and Soils*, p. 368.

base-forming metals, like sodium, potassium, calcium, magnesium, iron, and aluminium. These silicates are only very slightly soluble in water. While the amount dissolved may be exceedingly slight, it is nevertheless sufficient for the purposes here involved, if the time allowed is sufficiently long. For a given rock material the solubility, and hence the speed, of the weathering process increases with increasing fineness of the particles. Hence the fineness of the glacier flour renders it peculiarly suitable for rapid chemical conversion.

Like all salts of weak acids with strong bases, these silicates when dissolved react chemically with water, that is, hydrolyze, to form the free more or less ionized bases—the soluble hydroxides of sodium and potassium, the less soluble hydroxides of calcium and magnesium, the relatively insoluble hydroxide of iron, and either the free un-ionized silicic acid or some simple silicates. These simpler silicates continue to hydrolyze, if the reaction products are removed. There results the liberation of still other bases and in the end still simpler silicates, possibly kaolin, or even silica as quartz or sand.

If the reaction products are not removed by leaching, the dissolved materials soon attain a state of solution equilibrium. Under these conditions the decomposition products of one rock material may react with those of another to form more or less complex silicates of a secondary origin. Let the saturated solution be removed and fresh water added, the various solution equilibria are disturbed and the solution processes begin again.

The solution and subsequent hydrolysis of rock material, and the chemical reactions involved.—In the soil solution thus formed the dissolved materials will at the proper concentrations react with the carbon dioxide of the soil atmosphere to form the soluble, easily hydrolyzable carbonates of sodium and potassium and the slightly soluble carbonates of calcium and magnesium. These slightly soluble carbonates crystallize out as calcareous concretions, so frequently found in the clay subsoils. In the presence of an excess of carbon dioxide these insoluble carbonates pass into the soluble acid-carbonates and are leached away by the downward-moving free-water to lower depths, where they are again deposited in the form of concretions.

Ferrous silicates upon hydrolysis give ferrous ions. These may react with other ions of the soil solution to form the slightly soluble ferrous hydroxide or carbonate, or, what is more probable still, they may be immediately oxidized to ferric ions by the dissolved oxygen and then precipitated as the insoluble hydrated ferric oxide or basic carbonate.

Some may raise the question as to the possibility of the oxidation of the iron below the surface and out of contact with the air above. It must not be forgotten that by virtue of diffusion not only oxygen but also other dissolved gases tend to go just as far as the water does. Except at points where organic matter is undergoing decay, it is very doubtful if more than minimal traces of secondary ferrous compounds exist within or beneath the soil.

Crystalloids and colloids.—The resulting so-called weathering products may be grouped into two great general classes, namely, crystalloids and colloids. Crystalloids include all of the soluble acids, bases, and salts. They are simple in structure, that is, they exist in the dissolved state either as molecules or as ions. They are characterized by a relatively high diffusion speed and by the power to pass, though more or less slowly, through colloidal membranes. Nor is the colloidal membrane lacking in the soil; the clay itself may be considered as such a membrane.

Generally speaking, the term colloid is applied to all glue-like, gelatinous, amorphous substances. Strictly speaking, colloids represent suspensions of matter in an extremely fine state of subdivision, the suspended particles having diameters varying from $1\ \mu$ to $100\ \mu\mu$. The properties of colloids are primarily surface properties. The extent of surface development, and hence the magnification of specific properties, such as solubility, adsorption power, etc., may be seen from the following illustration: A centimeter cube of any solid substance, say platinum, exposes a surface of 6 square centimeters. Let this cube be divided successively and decimally to the dimensions of colloid particles. The total surface then exposed by the platinum will vary between 60 and 6,000 square meters.

Some colloidal properties involved in this problem.—Since colloids play an important rôle in the formation of soil strata and since they

impart to these strata many of their most important properties, it will be necessary to mention in detail some of the more important colloid properties and phenomena.

Colloids are divided into two general classes, namely, suspensoids and emulsoids. Briefly stated, suspensoids are suspensions of solid particles, chiefly inorganic, in a fluid medium; emulsoids are suspensions of fluid or semi-fluid particles. The emulsoids found in the soil are chiefly of organic origin, resulting from the secretions of animals, the exudations of plant roots, the humus, and other products of decaying organic matter brought about through the assistance of bacteria and fungi.

Colloids are also classified as reversible and irreversible. Most of the suspension colloids when desiccated, sometimes when frozen, or when in the presence of electrolytes, coagulate into a solid or semi-solid water-insoluble precipitate. When this solid is placed in water it does not again pass into suspension. It is therefore said to be irreversible. To this class belong the hydrated ferric oxide, the gelatinous silicic acid, the gelatinous, hydrated aluminum silicates, the clays, kaolin, etc. In rare cases one may find aluminum hydroxide.¹

Suspended colloid particles are either positively or negatively charged. Thus silicic acid, kaolin, and clay particles are negative; the basic hydrated ferric oxide is positive. These charged particles are precipitated by electrolytes, and it has been found that the precipitating power of the electrolyte is specifically a property of the ion bearing a charge opposite in sign to that of the particle. Further, the precipitating effect is greatest for those ions carrying the greatest number of charges.

Factors determining the stability of colloidal clay suspensions.—The effective properties of any colloid suspension depend upon its stability—its power to exist in the colloiddally suspended state. The stability is also one factor in the slow transportation of the colloid particles through the soil capillaries. This stability depends not only upon the absence of precipitating ions but also upon the potential difference between the charged particles and the oppo-

¹ Cameron and Bell, "The Mineral Constituents of Soil Solution," *U.S. Dept. of Agric., Bull.* 30 (1905), p. 22.

sitely charged solvent. The stability is greatest when this potential difference is greatest; its instability, or its tendency to coagulate, is greatest when this difference approaches zero.

Electrolytic coagulation or precipitation is preceded by the electrical adsorption of ions by the oppositely charged colloid particles. The precipitate carries with it the adsorbed ion or its salt, which in its adsorbed state is more or less difficultly removed by washing. Thus certain salts like those of potassium and ammonium are specifically and tenaciously held by the soil and clays, while the more toxic, less firmly adsorbed sodium salts are leached away.

When present in traces the singly charged H^+ and OH^- ions not only do not coagulate colloidal material but may even increase the stability of similarly charged colloid particles. In the hydrolytic decomposition of the alkaline silicates free OH^- ions are formed. These tend to increase the negative potential, likewise the stability of the negative colloids. Thus in the alkaline-soil solutions silicic acid and the colloidal hydrated silicates are kept to a slight extent, at least, in a state of pseudo-solution. Under the influence of the free carbonic acid and of mineral acids formed by adsorption cleavage of the dissolved salts there may be, as in acid soils, a slight excess of H^+ ions. These stabilize those colloidal "sols" containing positively charged particles. Thus colloidal hydrated ferric oxide is, to a very slight extent at least, rendered capable of transportation by the downward-moving free-water. In the initial stages of the leaching of an original silicate material, where the solution is distinctly alkaline, only the soluble salts and the transportable negative colloidal silicic acid are removed by leaching. Not until the alkalinity has disappeared would it be possible for the positively charged colloidal ferric hydroxide to exist in suspension. Iron in the colloidal form would be, therefore, almost the last colloidal material to undergo leaching.

A soil or clay colloid when once coagulated may again pass into the soluble hydrosol condition. Numerous experiments have been made dealing with this particular problem. Van Bemmelen has found that when finely divided clay is washed upon a filter the loosely bound coagulating salts are washed away. Upon further

washing, the clay becomes still more finely divided and finally passes through the filter, giving a turbid non-settling suspension. On adding a small amount of an electrolyte the milk-white liquid coagulates and settles. Upon washing again another point is reached at which the particles become infinitely fine and pass through. So it is in clay soils: an excess of water percolating downward removes the excess of coagulating electrolyte from the leached clay. This permits first a swelling of the reversible colloidal material and finally, to a slight extent at least, the gradual re-formation of the colloidal "sol." The suspended particles are thus permitted to pass slowly downward, where they are again coagulated at some lower level.

The inorganic colloids of soils and clays exhibit a marked tendency to adsorb upon their surfaces the various organic emulsoids formed from plant and animal *débris*. The humus is full of these. The adsorbed emulsoidal material forms an oil-like film about the suspended particles and imparts to them its own reversibility and stability. Hence when a mixture of the emulsoid and suspensoid materials are evaporated to dryness and the dry material is again placed in water the whole mass again passes into colloidal suspension. Furthermore, if emulsoidal material of any sort is added to a coagulated hydrogel, such as clay, the emulsoid possesses the power to peptizate or deflocculate the clay hydrogel, thus rendering it capable of colloidal suspension. By their reversible and protective influence humous materials hinder the coagulation of clay colloids; by their deflocculating influence they tend to make the hard, dry, sun-baked clays again reversible.

The terms humus and humic acid have been mentioned. The latter is a very complex substance of doubtful composition; it is an acid and possesses a colloidal nature. It dissolves in 8,337 parts of water at 6°. Its ammonium and magnesium salts are rather easily soluble; calcium humate dissolves in 3,125 parts of water, while the least soluble ferric humate dissolves in 5,000 parts. The humic acids are solvents for silica. Humic acid has the property¹

¹ Julien, "On the Geological Action of the Humic Acids," *Proc. Amer. Assoc. Adv. Sci.* (1879), pp. 311-410.

of gluing together vegetable earths into layers impervious to water. Their action consists mainly in the removal of calcium, magnesium, and iron, which are again precipitated at the lower limit of action, either by soluble salts, by exchange of bases, or by loss of water. The precipitated organic humus is finally oxidized and disappears, depositing the base metals as hydroxides or carbonates.

Summary of the mineral constituents of the soil solution.—In summarizing, the mineral matter of the soil solution may be divided into two classes. The more easily diffusible are those comprising the soluble alkali salts, the soluble acid-carbonates of calcium and magnesium, the slightly soluble ferrous compounds, the ferric humates, and the semi-colloidal sodium and potassium silicates. The less easily diffusible are the colloidal gelatinous silicic acid, the gelatinous hydrated silicates, and the colloidal hydrated ferric oxide. The solvent action of the alkaline-soil solution and of the humic acids, aided by the abrasive effects of the earth's displacements, slowly but surely transform the quartz pebbles into colloidal silica. Under the influence of the decaying organic matter the ferric compounds are reduced, temporarily at least, to ferrous compounds. While the existence of ferrous compounds in contact with the oxygenated soil atmosphere must obviously be a short one, the alternate oxidation and reduction permit the slow downward transportation of iron. The decomposition of the original complex aluminum silicates leads ultimately to the formation of the colloidal hydrated aluminum silicates. These are the most complex, most resistant, and the least soluble of all of the decomposition products produced by the disintegration of silicate rocks.

Hence in the leaching of the so-called weathering products of the original glacial till one should expect to find a gradual relative increase in the proportion of the soluble diffusible materials from the surface downward. On the contrary, conditions permitting, a gradual decrease in the proportion of alumina should be observed. This is exactly what is found from a study of the results of the chemical analyses of a complete series of strata in any single complete cut.

The kinds of materials analyzed and the localities from which they were taken.—The kinds of materials analyzed and the localities from which the materials were taken are as follows:

- A. Kansan gumbotil, and oxidized and leached Kansan till, from cut on the Chicago, Milwaukee & St. Paul Railway, about one mile east of Foster in the southeast corner of Monroe County, Iowa.
- B. Kansan gumbotil, oxidized and leached Kansan till, and oxidized and unleached Kansan till, from cut on the Chicago, Milwaukee & St. Paul Railway, at mile 372, one mile west of Murray, Clarke County, Iowa.
- C. Nebraskan gumbotil, Nebraskan oxidized and leached till, and Nebraskan oxidized and unleached till, from cut on the Chicago, Milwaukee & St. Paul Railway, one and one-half miles west of Manning, in the southwest one-quarter of section 18, Warren Township, Carroll County.
- D. Illinoian gumbotil, oxidized and leached Illinoian till, and oxidized and unleached Illinoian till from bluff north of Fort Madison, Lee County, Iowa.

The complete sections at each of the foregoing localities have already been given in this paper, but it seems well to bring them together here in relation to a discussion of the chemical analyses of materials:

A. Section in cut on the Chicago, Milwaukee & St. Paul Railway, about one mile east of Foster, in the southeast corner of Monroe County, Iowa:

	Feet	Inches
5. Soil, black, porous.....	2	
4. Loesslike clay, chocolate-colored, leached....	1	6
3. Loesslike clay, light-colored, grayish, on dry surface looks like gumbotil, has chocolate-colored stains, sticky when wet, contains a few small siliceous pebbles, leached.....	5	6
2. Gumbotil (Kansan), gray-colored, in lower part chocolate-colored; few pebbles; starchlike fracture when wet; leached.....	12	
1. Glacial till (Kansan), brown in color, with very irregular patches of gray-colored till resembling gumbotil; dry surface of the till is brownish-yellow; damp surface is chocolate-colored; few pebbles; leached to base of cut..	5	

B. Section in cut on the Chicago, Milwaukee & St. Paul Railway at mile 372, one mile west of Murray, Clarke County, Iowa:

	Feet
4. Loesslike clay, gray to pale-yellowish color on dry surface with irregular lines of brown; when damp it is grayish with mottling of yellow to brown colors; stands vertically, upper few feet mealy.....	15
3. Gumbotil (Kansan), gray to drab in color, sticky when wet, hard and tenacious when dry; contains a few siliceous pebbles; leached	11
2. Glacial till (Kansan), oxidized and leached..	4
1. Glacial till (Kansan), oxidized and unleached; has many lime concretions.....	11

C. Section in cut on Chicago, Milwaukee & St. Paul Railway, one and one-half miles west of Manning, in the southwest one-quarter of section 18, Warren Township, Carroll County, Iowa:

	Feet	Inches
6. Loess:		
Leached, yellowish-gray on dry surface; yellowish-brown to buff-brown on damp surface; no shells or concretions.....	7	
Unleached loess, lighter-colored on dry surface than the leached loess, and when damp it is buff with gray streaks. Contains shells and concretions.....	5	
5. Glacial till (Kansan), yellow, unleached, with calcareous concretions; numerous pebbles including granites, quartzites, etc. Below the oxidized, unleached till is gray drift with a few pebbles. It is gumbotil-like but effervesces freely. It was probably picked up from the gumbotil zone below.....	5	
4. Soil band containing carbonaceous material..		4
3. Gumbotil (Nebraskan), gray to drab-colored, few pebbles. The upper six feet is fine-grained, gray, and is less sticky and gumbotil-like than the lower seven feet, which is leached, but has some calcareous concretions.....	13	

	Feet	Inches
2. Glacial till (Nebraskan), oxidized, apparently leached, but has calcareous concretions, upon which are films of manganese dioxide.	2	
1. Glacial till (Nebraskan), unleached, oxidized, light-yellowish color on dry surface, mottled brownish with gray when damp, many calcareous concretions, especially in upper ten feet.	17	

D. Section in bluff north of Fort Madison, Lee County, Iowa:

	Feet	Inches
4. Loess and loesslike clay, grayish-yellow to buff-yellow.	7	
3. Gumbotil (Illinoian), drab to dark color; starchlike fracture; few pebbles; leached. . . .	4	6
2. Glacial till (Illinoian), oxidized, leached. . .	6	
1. Glacial till (Illinoian), oxidized, unleached to base.	15	

Chemical analyses of the Nebraskan, Kansan, and Illinoian gumbotils and their substrata.—The analytical data obtained from the chemical analyses of samples taken from localities at "A," "B," "C," "D" have been collected in the following tables. The results are given in two forms, (a) the percentage composition with respect to the less mobile constituents, (b) the parts by weight of these constituents per 100 parts of the more resistant Al_2O_3 .

TABLE I

A. Chemical analyses of Kansan gumbotil and oxidized and leached Kansan till from cut on the Chicago, Milwaukee & St. Paul Railway about one mile east of Foster, in the southeast corner of Monroe County, Iowa.

	a) PERCENTAGE COMPOSITION				
	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO
Gumbotil (Kansan).	72.03	4.18	12.27	1.33	2.29
Glacial till, oxidized, leached. .	73.11	4.62	11.57	1.66	2.56
	b) PARTS PER 100 PARTS Al ₂ O ₃				
	SiO ₂	Fe ₂ O ₃	CaO	MgO	
Gumbotil (Kansan).	587.0	34.10	10.84	18.68	
Glacial till, oxidized, leached. .	631.9	39.92	14.35	22.18	

TABLE II

B. Chemical analyses of Kansan gumbotil, oxidized and leached Kansan till, and oxidized and unleached Kansan till, from cut on the Chicago, Milwaukee & St. Paul Railway, at mile 372, one mile west of Murray, Clarke County, Iowa.

	a) PERCENTAGE COMPOSITION				
	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO
Gumbotil (Kansan)	70.46	4.17	12.04	1.21	0.55
Glacial till, oxidized, leached . .	71.84	4.62	10.86	1.29	0.72
Glacial till, oxidized, unleached	68.56	4.40	11.13	4.48	0.79
	b) PARTS PER 100 PARTS Al ₂ O ₃				
	SiO ₂	Fe ₂ O ₃	CaO	MgO	
Gumbotil (Kansan)	585.2	34.7	10.05	4.57	
Glacial till, oxidized, leached . .	661.5	42.5	11.87	6.66	
Glacial till, oxidized, unleached	616.0	39.5	40.30	7.16	

TABLE III

C. Chemical analyses of Nebraskan gumbotil, Nebraskan oxidized and leached till, and Nebraskan oxidized and unleached till, from cut on the Chicago, Milwaukee & St. Paul Railway one and one-half miles west of Manning, in the southwest one-quarter of section 18, Warren Township, Carroll County.

	a) PERCENTAGE COMPOSITION				
	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO
Gumbotil (Nebraskan)	71.59	4.35	12.79	1.26	0.93
Glacial till, oxidized, leached . .	66.85	5.92	11.65	3.67	0.78
Glacial till, oxidized, unleached	66.52	4.80	11.18	4.28	1.43
	b) PARTS PER 100 PARTS Al ₂ O ₃				
	SiO ₂	Fe ₂ O ₃	CaO	MgO	
Gumbotil (Nebraskan)	559.7	34.0	9.90	7.31	
Glacial till, oxidized, leached . .	573.8	50.7	31.51	6.71	
Glacial till, oxidized, unleached	594.5	42.9	38.30	12.81	

Table V shows the comparative results of the chemical analyses of "A," "B," "C," "D."

Discussion of the chemical data.—The three localities "A," "B," and "D" show the gumbotil underlying loess or loesslike clay covered by a thin layer of soil. At "C" the Nebraskan gumbotil lies below soil with no intervening loess or loesslike clay. The

TABLE IV

D. Chemical analyses of Illinoian gumbotil, oxidized and leached Illinoian till, oxidized and unleached Illinoian till, from bluff north of Fort Madison, Lee County, Iowa.

	a) PERCENTAGE COMPOSITION				
	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO
Gumbotil (Illinoian).....	71.07	4.24	14.91	0.79	0.85
Glacial till, oxidized, leached..	72.24	7.43	11.65	0.61	0.95
Glacial till, oxidized, unleached	72.30	3.47	8.59	4.13	1.28
	b) PARTS PER 100 PARTS Al ₂ O ₃				
	SiO ₂	Fe ₂ O ₃	CaO	MgO	
Gumbotil (Illinoian).....	476.0	28.44	5.34	5.68	
Glacial till, oxidized, leached..	620.1	63.80	5.26	8.22	
Glacial till, oxidized, unleached	841.2	40.39	48.10	14.95	

TABLE V

	A	B	C	D
SiO ₂				
Gumbotil.....	72.03	70.46	71.59	71.07
Glacial till, oxidized, leached.....	73.11	71.84	66.85	72.24
Glacial till, oxidized, unleached.....		68.56	66.52	72.30
Fe ₂ O ₃				
Gumbotil.....	4.18	4.17	4.35	4.24
Glacial till, oxidized, leached.....	4.62	4.62	5.92	7.43
Glacial till, oxidized, unleached.....		4.40	4.80	3.47
Al ₂ O ₃				
Gumbotil.....	12.27	12.04	12.79	14.91
Glacial till, oxidized, leached.....	11.57	10.86	11.65	11.65
Glacial till, oxidized, unleached.....		11.13	11.18	8.59
CaO				
Gumbotil.....	1.33	1.21	1.26	0.79
Glacial till, oxidized, leached.....	1.66	1.29	3.67	0.61
Glacial till, oxidized, unleached.....		4.48	4.28	4.13
MgO				
Gumbotil.....	2.29	0.55	0.93	0.85
Glacial till, oxidized, leached.....	2.56	0.72	0.78	0.96
Glacial till, oxidized, unleached.....		0.79	1.43	1.28

loess and loesslike clay are of great interest but are not being considered except incidentally in this paper. In places these materials are clearly eolian in origin. In other places the loesslike clay may be related closely in origin to the gumbotil. The presence of loess or loesslike clay above the gumbotil might be expected to have had some slight effect upon the present chemical composition of the gumbotil, and in fact may explain the few percentages in the analyses which might seem to contradict the theory proposed.

It is assumed that the composition of the flour of the unoxidized and unleached till is now the same as it was when laid down by the glacier. The possibility exists, however, that it may have received a small amount of leached material from above, or that it may have lost to the strata above by capillary flow slight quantities of the more easily diffusible dissolved materials. It is not to be expected that its composition will be similar to that of overlying materials which have been subjected to marked chemical changes, to leaching, or to infiltration.

Attention should be called again to the fact that the gumbotils occupy definite topographic positions and that, as a result of erosion subsequent to the formation of the respective gumbotils, the areas of gumbotil are now very limited compared with the extent of the former gumbotil plains.

A study of Tables I to IV will bring out several interesting facts. In all of the series here represented the percentage of Al_2O_3 decreases downward from the gumbotil through the oxidized and leached zone. Except in the case of "B" (Table II), this decrease continues also through the oxidized and unleached zone.

Perhaps the most important evidence in favor of the leaching theory is to be gained from a study of the relative proportions of CaO and MgO in the various horizons. In practically every series the proportions of these two constituents show a pronounced increase downward. Apparent contradictions for both might be considered for MgO in Table III and CaO in Table IV. Field relations will show in these instances either that the gumbotil is overlaid by material containing a higher proportion of these constituents, or that erosion began before the leaching process in the gumbotil was completed. Assuming that the loess or the loesslike

clay is a subsequent formation, it also will have been leached of some of its CaO and MgO. This means a slight increase in the proportions of these two in the stratum below, the leaching of which has not been completed.

The leaching process.—The silica and iron are less diffusible and hence less subject to leaching than are the carbonates of calcium and magnesium, and a much longer time is required for complete leaching. In every instance the proportion of iron in the gumbotil is less than it is in the oxidized and leached stratum just below. Except for the case of the Nebraskan (Table III), the proportion of SiO₂ is greater in the oxidized and leached stratum than in the gumbotil. It should be observed that the Nebraskan at locality "C" underlies the Kansan, and the apparent discrepancy may be accounted for in the transfusion of the alkaline silicates from the Kansan into the upper strata of the Nebraskan below. On the basis of parts per 100 parts of Al₂O₃, not only CaO and MgO but also SiO₂ show distinct evidence of leaching even in the oxidized and leached zone, and this is true for practically every series. On the same basis the evidence points to a leaching of the iron into the oxidized and leached zone from the gumbotil, but the time allowed was not sufficient for the subsequent leaching of the iron from the oxidized and leached zone into the one below. This is not surprising, since, as will be shown later, the iron is the last constituent to be leached away.

The oxygenated and carbonated water falls upon a uniformly level, more or less uniformly constituted, blue to blue-black drift. Percolating downward, it dissolves a portion of the rock material. Hydrolysis follows, and there are liberated successively the hydroxides of sodium or potassium, then of calcium or magnesium, and finally the more or less difficultly soluble hydroxides of ferrous and ferric iron, depending upon the nature of the iron in the original silicate. The ferrous iron throughout the depth penetrated by the dissolved oxygen is immediately oxidized and the deposit assumes the typical iron color of the yellow clays.

The calcium and magnesium hydroxides combine with the carbon dioxide of the soil atmosphere to form the insoluble carbonates. These crystallize out as calcareous concretions. The

soluble alkalies and the alkaline silicates are carried downward by the moving free-water. The negative colloidal silicates and silicic acid are coagulated and thus rendered motionless by the positively charged calcium and magnesium ions. As hydrolysis proceeds the mass of the insoluble material thus formed increases and probably does continue to increase until all of the easily available, hydrolyzable materials are used up or removed.

The second stage of the leaching process now follows. Obviously those insoluble substances which are most easily attacked will be the first to be leached away. These are the carbonates of calcium and magnesium. Although only very slightly soluble, the dissolved portions of these combine with the carbonic acid of the soil solution to form the soluble acid carbonates. These are carried downward to lower levels, where in fissures and crevices they again crystallize as irregular concretions. In this way were formed all of those calcareous concretions which are found in the oxidized zone.

According to the law of mass action, the activity, or the solvent effect, of the carbon dioxide will be greatest at points where its concentration is a maximum. This obviously will be at the upper level of the initially unleached calcareous zone. Owing to its diffusion power some of the carbon dioxide may escape combination at the upper level only to combine at a slightly lower level. Ultimately there will be a lower limit beyond which the carbon dioxide entering from the atmosphere will not penetrate, or its concentration in the soil solution will be too slight to produce any appreciable chemical effect. These two limits of maximum and minimum activity represent the boundaries of the dynamic zone of carbonic acid activity—the oxidized and leached zone. As time goes on the concretions at the upper level disappear, and the levels of maximum and minimum activity move downward simultaneously.

This dynamic zone has played an important rôle in all drift transformations. It spreads horizontally like a continuous sheet of more or less uniform thickness. It is found always directly upon the oxidized and unleached drift and directly below the gumbotil. In the Nebraskan drift it is thin, less than two feet to somewhat more than four feet. The oxidized leached zone of the

Kansan drift averages about five feet, attaining in a few places a thickness of about seven feet. That of the Illinoian has an average thickness not to exceed six feet.

After the leaching of the calcium and magnesium carbonates there follows a third step. When the concentrations of the precipitating calcium and magnesium ions have been reduced below their critical coagulating values new processes occur within the leaching zone. The coagulated iron passes into solution either as colloidal ferric hydroxide by peptization or deflocculation by the emulsoidal organic humous material or through the influence of peptizing ions, or as ferrous compounds by reduction by organic matter. Thus, either by colloidal flow, by alternate reduction and oxidation, or through the medium of its soluble or slightly soluble salts, the iron is leached and slowly passes downward. The silica either in the form of the colloidal gelatinous silicic acid or as the alkaline silicates also moves downward. Likewise, through various peptizing influences the colloidal clays and the simpler colloidal silicates begin to swell and deflocculate. Ultimately some of these pass into suspensions of colloidal particles. They are caught also in the downward current and carried by it to lower levels, where they are again coagulated. Only a very slight amount of this kind of material is leached away. There is left above only the more resistant, less mobile, complex colloidal aluminum silicates.

The stratum now forming, deprived of practically all of its sodium and potassium, of most of its calcium and magnesium, and some of its iron and silica, is the present residuum of the whole chemical leaching process. This is the gumbotil.

Physical and chemical properties of the gumbotils.—The properties of the gumbotil are largely those which one might predict from a knowledge of the colloidal chemistry of clays. Like certain colloids it becomes very hard and tenacious when dry; it swells when wetted and then to some extent passes spontaneously into colloidal suspension. It becomes sticky and sometimes so slippery that under the pressure of the earth above it oozes or slides out of the sides of the hills. It is gray when dry, dark when wet. The characteristic color changes of the gumbotil are those imparted to it

by the colloidal clays, perhaps the kaolin contained in it, the color of the colloidal material being sufficiently strong to mask the reddish-yellow color of any oxidized iron which may be present. This doubtless is responsible for the belief held by some persons that the iron in the gumbotil is deoxidized or reduced, a condition which could hardly be possible in the presence of the oxygenated soil solution.

The chemical analyses of the gumbotils from different drifts and localities show, with respect to certain constituents, a striking similarity. This is especially true for the iron and silica and, as we might expect, for the calcium. Slight fluctuations may be expected due to differences in the nature of the original rock materials, to the amount of rainfall, or to leaching from above. It may be concluded, therefore, that all gumbotils have a common origin—the chemical modification by weathering of glacial till.

Similarities of the gumbotils and the adjacent yellow oxidized and leached zones.—Furthermore, the chemical analyses, as arranged in Table V, show a slightly less striking similarity between the gumbotil and the yellow oxidized-leached clay. Naturally one should expect to find a slightly greater concentration of the diffusible material in the leached zone. One should expect also to find a slight variation in the proportion of any one constituent between the top and the bottom of any single zone. Each level in any one zone is still slightly unleached with respect to another level close to and above it.

The proportions of most of the constituents present in the oxidized-leached and gumbotil zones differ in most of the series by only a few tenths of 1 per cent. When greater deviations occur it can be shown that one or more of the upper strata have been removed before the leaching process was completed. The distinguishing features between these two strata are, therefore, due primarily to differences in the physical properties, and these properties are chiefly the colloidal properties of the clay itself. It is possible that two forms of the same material are being dealt with, namely, the gumbotil, a highly colloidalized form, and the oxidized-leached clay, the non-colloidalized form, that is, a form which in the presence of electrolytes is incapable of assuming

certain colloidal properties. In fact recent uncompleted work by Mr. L. B. Miller¹ gives evidence which not only supports the idea that these two zones differ chiefly in respect to differences in colloidal properties but also strongly confirms the theory that the gumbotil is directly related to the drift. It has already been stated that colloidal properties are primarily properties of the surface. A given colloid material of different degrees of subdivision will adsorb varying amounts of a given substance, and the amounts adsorbed by a given mass of the colloid will be approximately proportional to the specific colloidal surface. Assuming that hygroscopic water adsorbed by clays may be taken as a measure of colloidal property and of surface development, Miller has determined the amount of hygroscopic water taken up by each of these clays at 25°. He has found that, beginning with the original drift material the specific surface increases gradually, but at an increasing rate upward to the gumbotil. He has also determined the "total-water capacity," that is, the amount of water per gram which is just sufficient to cause the clays to "run." This likewise is greatest for the gumbotil in any drift, and it decreases gradually downward through the lower layers. The high "total-water capacity" of the gumbotil accounts for the ease with which it slides in exposed cuts.

SUMMARY

The aim of this paper has been to show by field and laboratory evidence that the gumbotils on Nebraskan, Kansan, and Illinoian glacial tills are the result chiefly of chemical weathering of drift. Thus far no distinctive evidence has been found in Iowa to indicate that the boulder clay from which gumbotil is thought to have been derived differed to any great extent from typical boulder clay. In the case of the Iowan and Wisconsin glacial tills, which are too young to have had a gumbotil developed on them, the till at and near the surface does not appear to differ in any important respects from the till which is deeper below the surface. In this connection it should be stated that Mr. E. W. Shaw, as a result of his studies of the Illinoian drift in southern Illinois, the Kansan drift in

¹ L. B. Miller, *The Colloidal Properties of Clays*.

northern Missouri, and other till sheets elsewhere, believes that the upper parts of the tills have been, from the times of deposition of the drifts, somewhat different from the middle and lower portions of the drift.¹

It should be stated that, although it is believed that gumbotil is essentially the result of chemical weathering of glacial till, it is recognized that wind action, freezing and thawing, burrowing of animals, slope wash, and other factors may have contributed to the formation of these gumbotils.

In a subsequent paper attention will be directed to the fact that the gumbotils, on account of their distinctive characters, wide distribution, and topographic positions, are the most satisfactory criteria that have yet been found for differentiating the older drifts. Furthermore, since the gumbotils are the result of changes which took place in interglacial times, they may be considered in relation to the problem of the relative durations of the interglacial epochs.

The gumbotils strengthen the view now generally accepted that the history of the Glacial Period involves, not a few thousand years but probably hundreds of thousands, and possibly millions, of years.

¹ E. W. Shaw, "Characteristics of the Upper Part of the Till of Southern Illinois and Elsewhere," *Abstract, Bull. Geol. Soc. Amer.*, Vol. XXIX (1918), p. 76.